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Simulations of the population of Centaurs – II. Individual objects

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ABSTRACT

Detailed orbit integrations of clones of five Centaurs – namely, 1996 AR20, 2060 Chiron, 1995 SN55, 2000 FZ53 and 2002 FY36 – for durations of ∼3 Myr are presented. One of our Centaur sample starts with perihelion initially under the control of Jupiter (1996 AR20), two start under the control of Saturn (Chiron and 1995 SN55) and one each starts under the control of Uranus (2000 FZ53) and Neptune (2002 FY36), respectively. A variety of interesting pathways are illustrated with detailed examples including: capture into the Jovian Trojans, repeated bursts of short-period comet behaviour, capture into mean-motion resonances with the giant planets and into Kozai resonances, as well as traversals of the entire Solar system. For each of the Centaurs, we provide statistics on the numbers (i) ejected, (ii) showing short-period comet behaviour and (iii) becoming Earth- and Mars-crossing. For example, Chiron has over 60 per cent of its clones becoming short-period objects, while 1995 SN55 has over 35 per cent. Clones of these two Centaurs typically make numerous close approaches to Jupiter. At the other extreme, 2000 FZ53 has ∼2 per cent of its clones becoming short-period objects. In our simulations, typically 20 per cent of the clones which become short-period comets subsequently evolve into Earth-crossers.

Key words: stellar dynamics – celestial mechanics – Kuiper belt – minor planets, asteroids – planets and satellites: general.

1 INTRODUCTION

The Centaurs are a transition population of minor bodies between the trans-Neptunian objects and the Jupiter-family comets (see, for example, Horner et al. 2003, and the references therein). Centaurs typically cross the orbits of one or more of the giant planets and have relatively short dynamical lifetimes ($\sim 10^6$ yr). Their properties are exemplified by the first known Centaur, Chiron, which was found in 1977 on Palomar plates (Kowal, Liller & Marsden 1979). Chiron is a large minor body with perihelion close to or within the orbit of Saturn and aphelion close to the orbit of Uranus. The Centaurs have so far largely eluded the attention of numerical integrators. The only ones that have hitherto been the subject of detailed dynamical investigations are Chiron itself (Hahn & Bailey 1990; Nakamura & Yoshikawa 1993) and Pholus (Asher & Steel 1993). Dones, Levison & Duncan (1996) also looked briefly at four Centaurs, including Chiron and Nessus. All these investigations were for durations of less than 1 Myr and involved modest numbers of clones.

Horner, Evans & Bailey (2004, hereafter Paper I) integrated the orbits of 23 328 clones of 32 selected Centaurs and used the data set to evaluate statistical properties of the Centaurs in a model Solar system containing the Sun and the four giant planets. Hence, these longer numerical integrations with larger numbers of clones provide better statistics and highlight some unusual past histories and future fates for Centaurs. In this companion paper, the behaviour of clones of five of these Centaurs – namely, 1996 AR20, Chiron, 1995 SN55, 2000 FZ53 and 2002 FY36 – are studied in more detail. The objects are chosen to span a wide range of properties. 1996 AR20 has the shortest half-life in our sample, while 2000 FZ53 has the longest half-life. 1995 SN55 is the Centaur with the brightest absolute magnitude (hence potentially the largest Centaur known), while Chiron is the only one confirmed to display cometary out-gassing.

Horner et al. (2003) introduced a new classification system for cometary-like bodies according to the planets under whose control the perihelion and aphelion lie. For example, we classify Chiron as an SU object, by which we mean that the position of its perihelion lies within the zone of control of Saturn, and that the position of its aphelion lies within the zone of control of Uranus. It is apparent that perturbations at perihelion, by Saturn, will act primarily to move the position of the aphelion, and vice versa. In other words, the motion near Saturn determines whether or not the body gets to Uranus, or is captured to a more tightly bound orbit, or expelled. Conversely, perturbations by Uranus, near aphelion, largely determine the future

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perihelion distance. So, in a wider sense, Saturn also 'controls' the aphelion (and Uranus the perihelion), as it determines its numerical value. However, in this paper, whenever we talk of a planet controlling a minor body at perihelion (or aphelion), we mean that the motion at perihelion (or aphelion) lies in the zone of control of that planet.

For our selected five Centaurs, there is one object with perihelion under the control of Jupiter (1996 AR20), two under the control of Saturn (Chiron and 1995 SN55), and one each under the control of Uranus (2000 FZ53) and Neptune (2002 FY36). Clones of the objects were created by incrementally increasing (and decreasing) the semimajor axis a of the object by 0.005 au, the eccentricity e by 0.005, and the inclination i by $0\overset{\circ}{.}01$. Nine values were used for each of these elements, with the central (fifth) value of the nine having the original orbital elements for the Centaur, as taken from The Minor Planet Centre. The other orbital elements aside from a, e and i are unchanged (see Paper I for more details). This procedure yielded 729 clones of each Centaur, all of which were numerically integrated for up to 3 Myr. In this paper, we restrict ourselves to just two particularly interesting clones for each Centaur.

Although all five of our selected Centaurs have reasonably reliable ephemerides, only Chiron has been the subject of sustained interest from observers. For Chiron, there are long-term photometric studies of the behaviour of the object (Duffard et al. 2002), detailed analyses of its reflectance spectrum (Foster et al. 1999), as well as the use of archival pre-discovery images of the object (Bus et al. 2001). There are little observational data on the remaining four objects.

The detailed studies of individual clones of these objects are important to illustrate some of the dynamical pathways in the Solar system. Objects in very stable regimes in the Solar system (such as some resonances) are long-lived and could be potential targets for new surveys. A good example is the possible long-lived belt of objects between Uranus and Neptune claimed by Holman (1997). Objects in unstable regimes must evolve, and correlations between observables and orbital properties are then expected. For example, bluer colours might indicate a younger, fresher surface and so be indicative of recent cometary activity. So, a Centaur with blue colours (such as Chiron) could be a candidate for a passage through a cometary phase in the recent past. Individual examples allow us to match an orbital history to such a presumed pathway.

The paper is organized according to object, with 1996 AR20 studied in Section 2, Chiron in Section 3, 1995 SN55 in Section 4, 2000 FZ53 in Section 5 and 2000 FY36 in Section 6.

2 EVOLUTION OF A JN OBJECT: 1996 AR20

1996 AR20 is a JN object with its perihelion under the control of Jupiter and its aphelion under the control of Neptune. Among the Centaurs, 1996 AR20 has the shortest known half-lives, namely 540 kyr in the forward and 594 kyr in the backward direction. Its orbit is interesting as its initial position lies close to two prominent mean-motion resonances. The initial value of the semimajor axis in the integrations was 15.2 au, which is within 0.02 au of the 1 : 5 mean-motion resonance with Jupiter and within 0.06 au of the 1 : 2 mean-motion resonance with Saturn. In addition, 1996 AR20 has an eccentricity of 0.627 so that it can approach all the major outer planets close enough to be perturbed. These factors all contribute towards making 1996 AR20 one of the least stable Centaurs. Of the 729 clones, 62 become Earth-crossers, 154 become Mars-crossers and 340 become short-period comets in the forward integration. These numbers are all slightly larger in the backward integration, namely 89, 194, and 406, respectively.

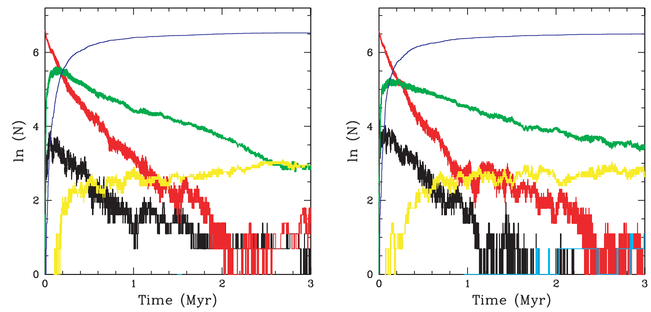

Figure 1. The evolution of the population of clones of 1996 AR20 subdivided according to the planet controlling the perihelion (objects controlled by Jupiter, Saturn, Uranus and Neptune are red, green, yellow and cyan, respectively). Also shown are the evolution of the number of short-period comets (black), trans-Neptunian objects and ejected objects (blue). The left panel shows the results from the forward integration, the right the backward integration. (This colour convention is employed in all subsequent plots of this nature.)

Fig. 1 shows how the population of clones of 1996 AR20 changes over time. Initially, all 729 clones have perihelion under the control of Jupiter, but by the end of the simulation, in both the forward and backward directions, over 650 of the clones have been ejected. The number of objects under the control of Jupiter rapidly decays, with most either being ejected, or moving to the control of Saturn, or transferred to cometary orbits. The numbers in each of these classes peak early within the simulation and then decay as more and more objects are ejected. Only a small number of clones of 1996 AR20 evolve so that the perihelion is under the control of Uranus and Neptune. The great majority of objects are ejected by either Jupiter or Saturn, giving very few the opportunity to evolve all the way out to Neptune.

2.1 A source for Jovian Trojan asteroids

Fig. 2 shows the evolution of the 12th clone[1] of 1996 AR20, integrated in the forward direction. The initial semimajor axis, eccentricity and inclination of this clone are $a = 15.177$ au, $e = 0.617$ and $i = 6\overset{\circ}{.}17$. The clone is rapidly captured into a 1:1 mean-motion resonance with Jupiter, which it then occupies for over 0.5 Myr before ejection from the Solar system. The clone displays quite large variations in a, e and i while in the resonance. By plotting the positions over time, it is clear that the clone follows a tadpole orbit librating about the Lagrange point. This is significant as it shows that Centaurs can be captured into the 1 : 1 resonance with Jupiter. Hence, there may well be Jovian Trojans that were originally Centaurs and vice versa. It would be interesting to see whether any Jovian Trojans display cometary out-gassing, since recently captured Centaurs may still contain volatiles, while any Trojans captured from an original Main Belt asteroidal orbit are unlikely to display such activity.

In our Centaur orbital integrations, we find that clones are quite frequently trapped into 1 : 1 mean-motion resonances with all the giant planets.

2.2 A collision with Saturn

Fig. 3 shows the behaviour of the 66th clone of 1996 AR20, whose initial orbital elements were $a = 15.177$ au, $e = 0.617$, $i = 6\overset{\circ}{.}23$

[1] The clone label is useful for our internal data management but carries no other physical meaning.

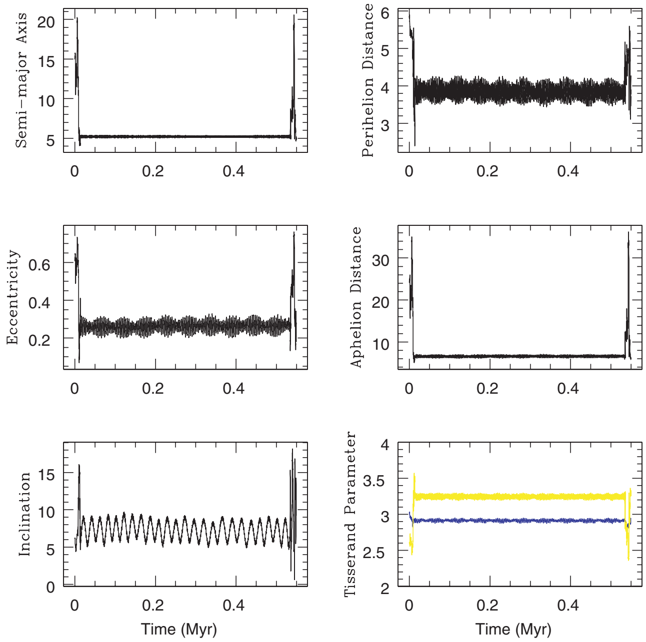

Figure 2. The evolution of the 12th clone of 1996 AR20 in the forward direction. Subpanels show the evolution of semimajor axis, perihelion and aphelion distance (all in au), inclination (in degrees) and eccentricity. In the plot of the Tisserand parameter, the value of T_J is plotted in blue and T_S in yellow. This convention is followed in all similar plots. Note that the clone is rapidly trapped into a 1 : 1 mean-motion resonance with Jupiter until ejection after ∼0.5 Myr.

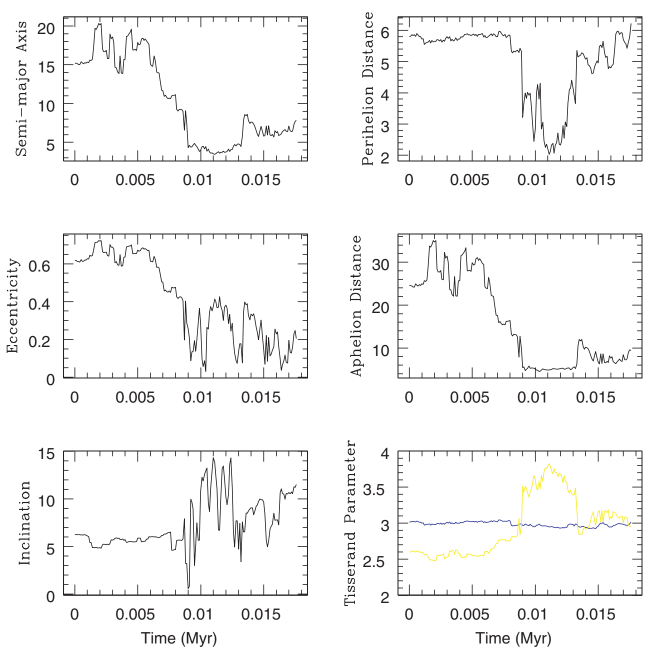

Figure 3. The evolution of the 66th clone of 1996 AR20 in the forward direction. The clone hits the surface of Saturn after 18 kyr.

(almost the same as the 12th clone!). The 66th clone impacts upon Saturn at the end of its lifetime, 18 kyr after the start of the integration. In Paper I, we calculated that Centaurs impact onto the surface of Saturn at a rate of 1 every 28 kyr. The perihelion of the clone starts the simulation under the control of Jupiter, and perturbations by this planet cause a number of changes in the semimajor axis of the clone. Finally, a series of close encounters reduces the perihelion and aphelion distances for the object until it twice becomes a cometary body (at around 12 kyr, very briefly, and then for a more prolonged period from 13 to 15 kyr). After this, the perihelion and aphelion distances of the clone increase until the perihelion lies just beyond the orbit of Jupiter and the aphelion lies under the control of Saturn. The object finally collides with Saturn at aphelion, roughly 18 kyr from the present.

3 EVOLUTION OF A SU OBJECT: CHIRON

Chiron was the first Centaur to be discovered in 1977. Pre-discovery images allow the orbit to be traced all the way back to the perihelion passage of 1895 (see Kowal et al. 1979). Chiron has a coma which undergoes variations in brightness (Meech & Belton 1989; Luu & Jewitt 1990). The photometric activity of Chiron is sporadic and apparently unrelated to heliocentric distance (Duffard et al. 2002). For example, the increase in brightness during 1988–1991 (e.g. Tholen et al. 1988) was followed by a period of minimal activity as the object passed through perihelion in 1996. Also unusual is the size of Chiron – with an absolute magnitude H of 6.5, it is one of the largest Centaurs (only Chariklo and 1995 SN55 are brighter). The object has a half-life of 1.03 Myr (forwards) and 1.07 Myr (backwards). In the forward simulation, 415 objects become short-period objects, of which 84 become Earth-crossing and 180 become Mars-crossers. In the backward simulation, these numbers are slightly larger at 445, 110 and 208, respectively. In other words, significantly more than half of the clones become short-period comets at some point within their evolution, suggesting that it is quite likely that Chiron has been a cometary object at some point in the past and may well become one again in the future. This ties in well with the work of Hahn & Bailey (1990), although they found a much greater discrepancy between the likelihoods of the object being a short-period comet in the future and in the past. Fig. 4 shows how the overall population of clones of Chiron changes over time. Over the period of the integration, around 600 clones are ejected in both the forward and backward integrations.

3.1 A long-lived short-period comet

Fig. 5 shows the evolution of the 206th clone of Chiron, which started the integrations with $a = 13.591$ au, $e = 0.394$ and $i = 6.^{\circ}90$. This clone displays short-period cometary behaviour for almost 1 Myr. During the early part of the evolution, encounters act to reduce its perihelion distance so that it comes under the control of Jupiter. Once

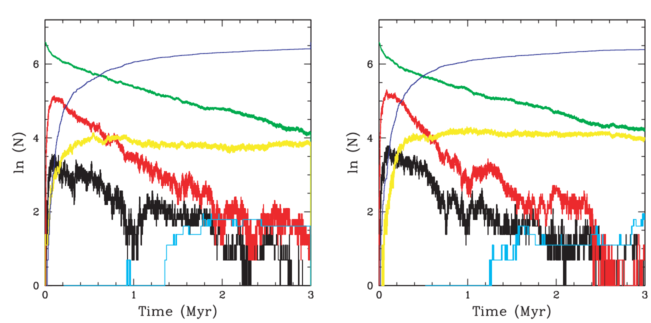

Figure 4. The numbers of clones of Chiron controlled by Jupiter (red), Saturn (green), Uranus (yellow) and Neptune (cyan), together with the numbers of short-period comets (black), trans-Neptunian and ejected objects (blue), plotted against time. The left (right) panel shows the results from the forward (backward) integration.

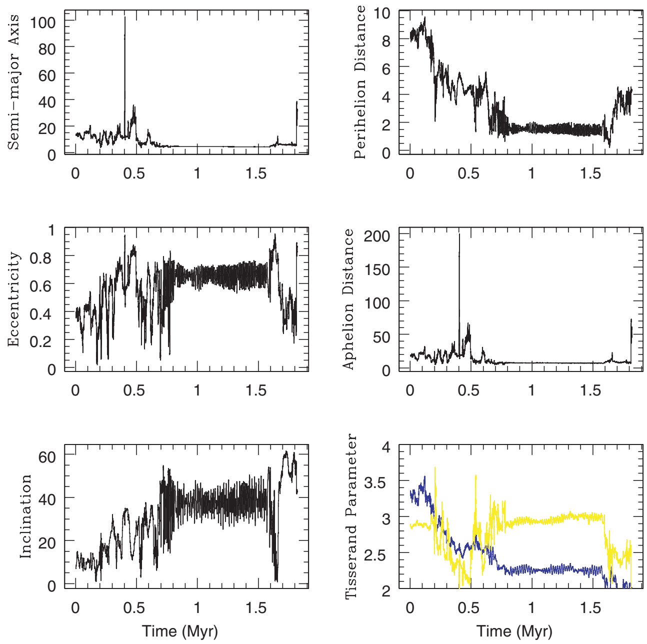

Figure 5. The evolution of the 206th clone of Chiron in the forward direction and eccentricity. In the plot of the Tisserand parameter, the value of T_J is plotted in blue and T_S in yellow. Note the prolonged spell (∼1 Myr) as a short-period comet.

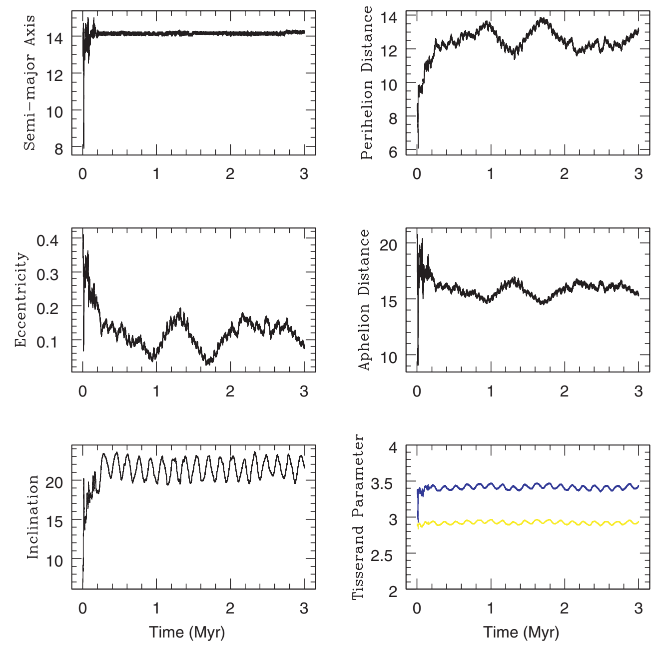

Figure 6. The evolution of the 78th clone of Chiron in the forward direction. Note the stable, nearly constant behaviour of the orbital elements as the clone is transferred to a long-lived orbit.

this happens, the behaviour of the object becomes more chaotic, leading to a near-ejection at 400 kyr, together with a number of short spells as a short-period comet (e.g. at 200 kyr). Finally, at around 700 kyr, the object is transferred into a cometary orbit of short-period. At 800 kyr, the object is captured into an orbit close to the 6 : 5 mean-motion resonance with Jupiter and the 3 : 1 mean-motion resonance with Saturn. After around 50 kyr in this resonance, the semimajor axis of the clone is reduced to slightly less than 4.5 au, and the object enters the 5 : 4 mean-motion resonance with Jupiter, which it occupies for approximately 350 kyr. After this time, the semimajor axis gradually decreases to smaller and smaller values, until at around 1.3 Myr the object enters the 4 : 3 resonance with Jupiter. It leaves this resonance briefly at the 1.4-Myr mark, but then re-enters it at around 1.45 Myr. Over all this time, the eccentricity and inclination of the clone experience rapid oscillations, with the inclination at times reaching over 50°. The perihelion and aphelion values also oscillate wildly, although the object only becomes Earth-crossing at the end of its time as a short-period comet. Shortly after this, encounters with Jupiter act to raise the perihelion distance slightly and eject it from the Solar system. The amount of time spent as a cometary object for this clone, at ∼1 Myr, is fairly exceptional. However, it does show that there is scope for Centaurs to be captured into short-period cometary orbits for very long periods. As Hahn & Bailey (1990) first emphasized, this is interesting and worrisome – an object the size of Chiron occupying a short-period cometary orbit for this period of time would pollute the inner Solar system with huge amounts of dust and debris. Though such long-term captures are uncommon, they are not by any means unusual within our sample of clones.

3.2 A very stable resonant orbit

Fig. 6 shows the orbital evolution of the 78th clone of Chiron, which had initial orbital elements of $a = 13.581$ au, $e = 0.384$ and $i = 6\overset{\circ}{.}94$. This clone is almost immediately captured into a very stable orbit, at around a semimajor axis of 14.15 au, in which it remains for the duration of the 3-Myr integration. The 5 : 9 resonance with Saturn lies at ∼14.2 au. Of course, the 2 : 9 resonance with Jupiter also lies at roughly the same location, but its effect is likely to be weaker on account of the high order of the resonance and the large perihelion distance of the clone. It is interesting that, during the period of stable behaviour, the inclination displays very smooth cyclical variations, between around 20° and 24°, while the eccentricity (and hence the perihelion q and aphelion Q distances) display variations which are much less regular. Throughout the stable period, the clone has a low eccentricity and hence orbits entirely between Saturn and Uranus. This is another illustration of the point made by Holman (1997) and Evans & Tabachnik (1999), namely that low-eccentricity orbits between the planets can be very stable.

4 EVOLUTION OF A SE OBJECT: 1995 SN55

1995 SN55 is an intriguing object that is surely worthy of more study from observers – if only in the first instance to recover it! It is only known from observations covering an arc of 36 d. According to its absolute magnitude ($H = 6.0$), 1995 SN55 is the largest of the Centaurs, with a diameter somewhere between 170 and 380 km (see, e.g. table 2 of Paper I). In addition, it has a high eccentricity ($e = 0.663$), which means that at perihelion the object lies 7.9 au from the Sun, while at aphelion, it reaches out to 39.2 au. The half-life is 0.701 Myr in the forward and 0.799 Myr in the backward direction. In the forward integration, 250 of the initial 729 objects became short-period comets at some point, with 50 becoming Earth-crossing and 112 becoming Mars-crossing. In the backward integration, these numbers are slightly larger at 278, 55 and 118, respectively. Fig. 7 shows how the overall population of clones of 1995 SN55 changes over time. The unstable nature of this object is shown clearly in the rapid rate at which clones are ejected. In both forward and

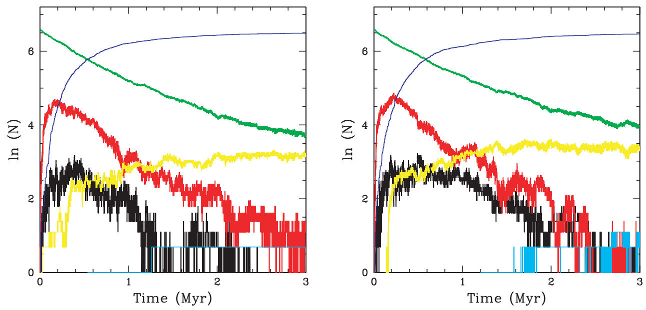

Figure 7. The numbers of clones of 1995 SN55 controlled by Jupiter (red), Saturn (green), Uranus (yellow) and Neptune (cyan), together with the numbers of short-period comets (black), trans-Neptunian and ejected objects (blue), plotted against time. The left (right) panel shows the results from the forward (backward) integration.

backward integrations around 650 of the clones are removed from the simulations by their end at 3 Myr.

4.1 A source for Earth-crossers

Fig. 8 shows the evolution of the 103rd clone of 1995 SN55. This clone has initial orbital parameters of $a = 23.549$ au, $e = 0.658$ and $i = 4\overset{\circ}{.}98$. It spends a prolonged spell of time as a short-period object, during which it approaches the orbit of the Earth closely and actually becomes Earth-crossing near the end of its short-period lifetime. In its early evolution, the clone experiences a number of changes in semimajor axis, due mainly to encounters with Saturn around perihelion. A particularly close encounter with Saturn at around 90 kyr reduces the aphelion distance Q from ∼60 au to below 30 au. This encounter is visible as a clear discontinuity in the plots for a, e and Q. After this, perturbations act systematically to reduce the perihelion distance, until the object enters the sphere of control of Jupiter. Then, a deep encounter at Jupiter reduces the perihelion distance still further to ∼2 au. For a further 40 kyr, the object moves on a chaotic orbit controlled by Jupiter, until at around 240 kyr, it is captured into a 2 : 1 mean-motion resonance with Jupiter in which it resides for ∼150 kyr. This is almost identical to the 5 : 1 mean-motion resonance with Saturn. The rough 5 : 2 commensurability of Jupiter and Saturn clearly plays an important role in providing a pattern of stable niches in which objects can survive for long periods of time.

At the beginning of the stay in the resonance, the eccentricity and inclination of the clone (and hence the perihelion q and aphelion Q distances) vary erratically. After ∼20 kyr, they become more stable, and start to display gradual, long-term variations. This is most obvious in the inclination of the clone, which is gradually pumped from a few degrees to two peaks of around 36°. After some 340 kyr, the behaviour of e and i begins to cycle far more rapidly, leading to equally rapid fluctuations in the behaviour of q and Q. Finally, at around 400 kyr, the clone leaves the mean-motion resonance, and moves inwards to become Earth-crossing. Towards the end of its life, the clone becomes Sun-grazing. However, the simulation is not trustworthy at very small q, owing to the fixed time-step of 120 d (see Paper I). None the less, it would be interesting to understand the effects of the impact of ∼100-km sized Centaurs (like 1995 SN55) on the Sun itself, for example, in terms of enhanced metallicity and increased reconnection effects.

4.2 A stable end-point in the outer Solar system

Fig. 9 shows the behaviour of the 160th clone of 1995 SN55, which has initial orbital elements of $a = 23.549$ au, $e = 0.673$ and $i = 5\overset{\circ}{.}04$. During the first 400 kyr of the evolution of this clone, it undergoes significant changes in its orbit, due mainly to the effects of Jupiter and Saturn. At one point (just before the 200-kyr mark), the perihelion of the clone dips very briefly to a mere 4 au, before rising again. While the object is being perturbed in this way, it experiences a fairly rapid rise in inclination, from the initial value of around 4° to a peak over 30°. After 400 kyr, the changes in the orbital elements of

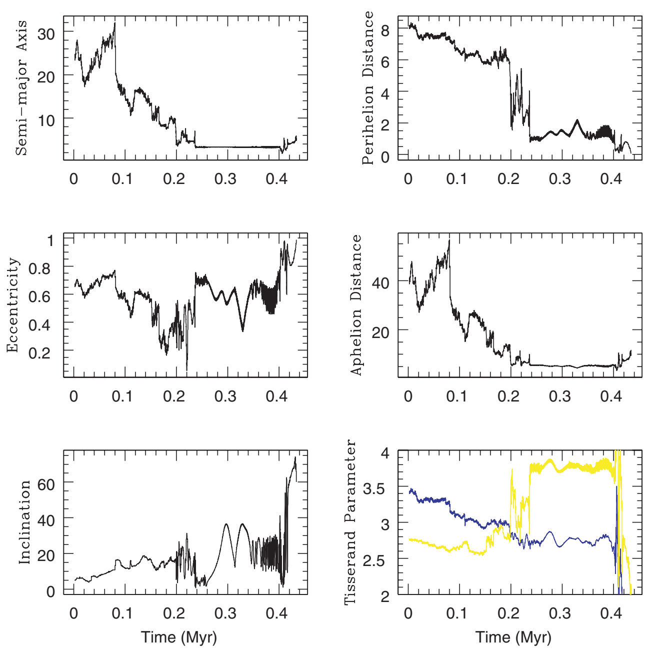

Figure 8. The behaviour of the 103rd clone of 1995 SN55 in the forward direction. In the plot of the Tisserand parameter, the value of T_J is plotted in blue and T_S in yellow. Note the spell as a short-period comet, Earth-crosser and finally Sun-grazer.

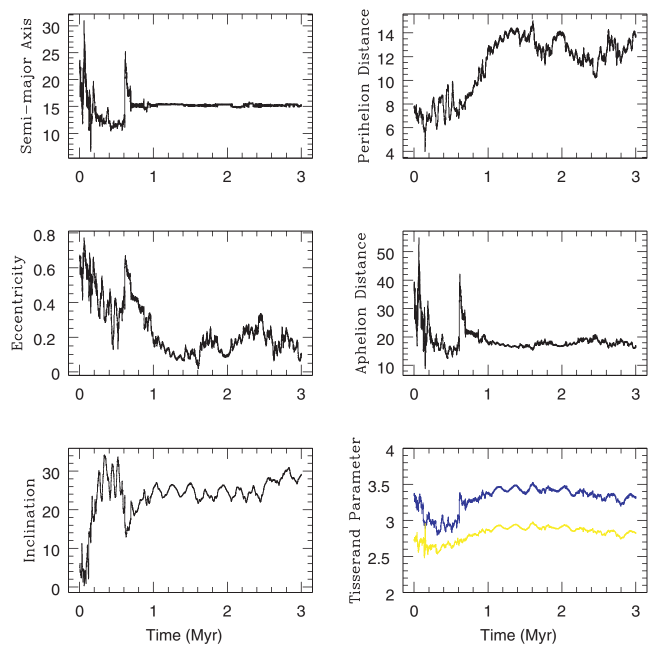

Figure 9. The orbital evolution of the 160th clone of 1995 SN55 in the forward direction. Note that the endpoint of the evolution of the clone is an orbit that lies almost entirely between Saturn and Uranus and is quite stable.

the clone become less severe, with the exception of one large 'kick' given at perihelion by Saturn, just after the 600-kyr mark. Shortly after this, the object falls into a stable orbit with $a \approx 15$ au. It then spends the remainder of the integration in this region of the Solar system. For the bulk of its stay, the clone has a semimajor axis of between 15 and 15.5 au. In this region, there are a number of mean-motion resonances which may be important in the behaviour of this clone. First, the 1 : 5 resonance with Jupiter lies at about 15.22 au, and the 1 : 2 resonance with Saturn lies at about 15.14 au. Between 1.4 and 1.8 Myr, and again around 2.5 Myr, the clone lies in a region overlapping both of these resonances, at a value of semimajor axis very similar to that occupied today by the most unstable object studied in our integrations, 1996 AR20 (discussed in Section 2). The difference between this clone of 1995 SN55 and the clones of 1996 AR20 lies in the eccentricity and inclination of the objects. While 1995 SN55 is near the resonances, its eccentricity is so low that at times it orbits entirely between Saturn and Uranus. This makes the orbit more stable than that of 1996 AR20, which lies on a highly eccentric orbit. In addition, the moderately high inclination of this clone through this period (i never falls below 22° in the final 2 Myr of the integration) helps to keep the clone stable.

When the clone is not in resonance with Jupiter and Saturn, it falls into the 7 : 5 resonance with Uranus (for example, between 1.1 Myr and 1.4 Myr). The apparent untidiness in the behaviour of the orbital elements during the final 2 Myr of the integration, given the stable nature of the orbits occupied, is a result of the overlap between the resonances. With whichever planet the clone is resonant at a particular time, there will be near-resonant effects from the others involved. This may explain the rapid, small variations in e, q and Q, which are far more pronounced than those seen in clones which occupy other resonances (for example, compare it with the behaviour shown in Fig. 2).

5 EVOLUTION OF A UE OBJECT: 2000 FZ53

At the start of the simulation, 579 of the clones fall under the control of Uranus at perihelion and are UE objects. The remaining 150 of the 729 clones fall under the control of Saturn at perihelion and are SE objects. The distribution of the clones in a–e–i space actually straddles the boundary between UE and SE. 2000 FZ53 is the Centaur with the longest known half-life – approximately 26.8 Myr in the forward and 32.3 Myr in the backward directions. It is also the object which lies on the most highly inclined orbit of those studied ($i = 34\overset{\circ}{.}9$). This is a contributing factor to the longevity of the object. Of the 729 clones in the forward direction, only 18 become short-period comets, and a mere five become Earth-crossing. In the backward direction, only 12 of the clones became short-period, with again five becoming Earth-crossing.

Fig. 10 shows how the overall population of clones of 2000 FZ53 changes over time. The extreme stability of this object is evidenced by the remarkably small number of the clones which are ejected by the end of the simulation. After 3 Myr, less than 50 of the initial 729 clones have been ejected in either direction of integration. A particularly interesting feature is the extent to which the populations of the object under the control of Uranus and of Saturn are coupled. This is caused by the flexing of the orbit, and hence the associated population of clones, under secular evolution. It is a consequence of the starting configuration in which clones lie across the boundary between SE and UE objects. Very few of the clones evolve inwards sufficiently to be controlled by Jupiter, or outwards to reach Neptune.

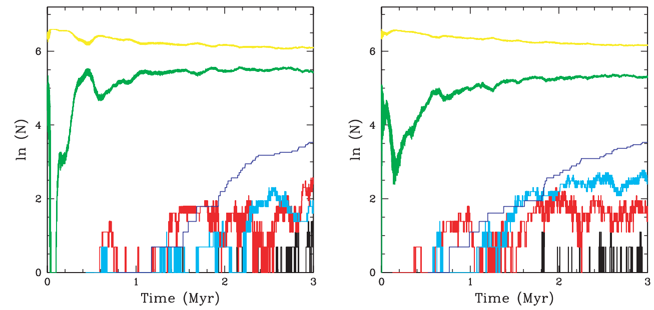

Figure 10. The numbers of clones of 2000 FZ35 controlled by Jupiter (red), Saturn (green), Uranus (yellow) and Neptune (cyan), together with the numbers of short-period comets (black), trans-Neptunian and ejected objects (blue), plotted against time. The left (right) panel shows the results from the forward (backward) integration.

5.1 A Kozai resonance

Fig. 11 shows the evolution of the 318th clone of 2000 FZ53. This has starting orbital elements of $a = 23.670$ au, $e = 0.469$ and $i = 34\overset{\circ}{.}94$. The clone spends the first 400 kyr in various fairly stable orbits, changing occasionally through distant encounters with Uranus and Neptune. These encounters lead to a gradual circularization of the orbit, pulling the eccentricity down from a value close to 0.5 at the start of the integration to a value just below 0.2. This decrease in eccentricity causes the perihelion distance to move outwards towards Uranus, and the aphelion distance to fall to that of Neptune. Eventually, the clone drops into a stable 3 : 4 mean-motion resonance with Uranus, which it occupies for around 2.2 Myr. During this time, the clone experiences no secular changes in its semimajor axis but there are coupled variations in eccentricity and inclination such that e is a maximum when i is a minimum. This

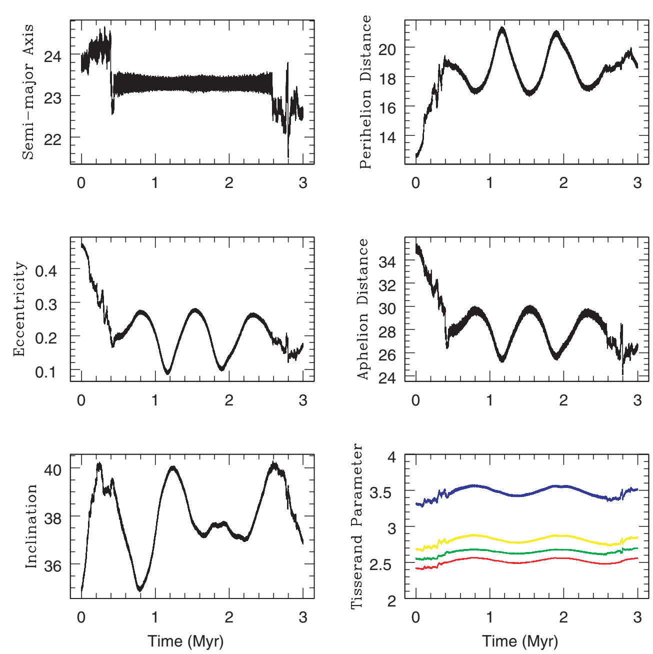

Figure 11. The behaviour of the 318th clone of 2000 FZ53 in the forward direction. In the plot of the Tisserand parameters, the value of $T_{\rm J}$ is shown in blue, $T_{\rm S}$ in yellow, $T_{\rm U}$ in red and $T_{\rm N}$ in green. Note the coupled variations in eccentricity and inclination (with the maxima of one corresponding to the minima of the other). This is characteristic of a Kozai resonance.

is characteristic of an object undergoing a Kozai resonance (Kozai 1962; Murray & Dermott 1999), for which the Kozai integral I_K

$$I_K = \sqrt{1 - e^2} \cos i \qquad (1)$$

remains constant. This can be confirmed by examining the value of $\omega_{\rm dif} = \omega - \omega_{\rm N}$ (the difference between the argument of pericentre for the object and Neptune). This is librating rather than circulating, consistent with trapping in the Kozai resonance.

5.2 A mean-motion resonance with Uranus

Fig. 12 shows the evolution of the 334th clone of 2000 FZ53. This clone has initial orbital elements of $a = 23.675$ au, $e = 0.459$ and $i = 34\overset{\circ}{.}87$. The first 1 Myr of the evolution is characterized by a number of protracted stays in stable orbits with semimajor axes between 23.5 and 25 au. There is a Kozai resonance in the first 400 kyr, during which the e and i of the clone vary in the familiar coupled fashion. This is followed by a couple of small transitions, until the clone arrives at a semimajor axis of just over 24.5 au. After the first 1 Myr, the clone experiences a series of fairly distant encounters with both Uranus and Neptune, which change the semimajor axis, until after 1.4 Myr, the clone enters the 3 : 5 mean-motion resonance with Uranus, in which it stays until the end of the simulation. While in this resonance, the eccentricity of the object is slowly driven down, raising the perihelion ever closer to the orbit of Uranus.

6 EVOLUTION OF AN OBJECT: 2002 FY36

Of all the objects studied in Paper I, the only one to be controlled by Neptune at perihelion is 2002 FY36. This Centaur lies on a low-eccentricity orbit (in fact, it is the most circular of the seed orbits for the integrations, with an eccentricity of 0.114). 2002 FY36 is amongst the most stable of the Centaurs, with half-lives of 12.5 Myr and 13.5 Myr in the forward and backward directions, respectively. In the forward simulation, only 78 of the clones of this object become short-period objects, with 16 becoming Earth-crossing and 35 becoming Mars-crossing. In the backward integrations these numbers are 68, 16 and 33, respectively. Fig. 13 shows the changing populations of clones within the simulation of 2002 FY36. The stability of the object is evidenced both by the very slow decay of clones under the control of Neptune (around 50 per cent of the clones are still controlled by Neptune at the end of the simulation), together with the very slow ejection rate (less than 100 clones are ejected in both the forward and backward integrations).

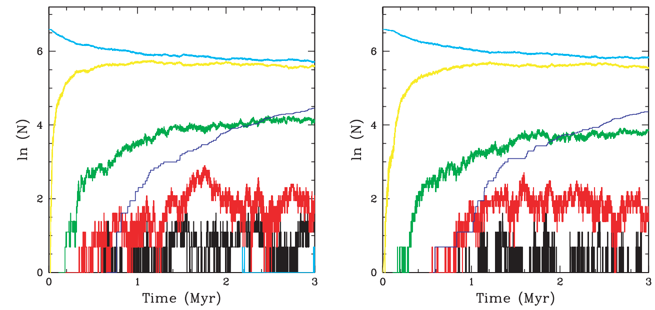

Figure 13. The numbers of clones of 2002 FY36 controlled by Jupiter (red), Saturn (green), Uranus (yellow) and Neptune (cyan), together with the numbers of short-period comets (black), trans-Neptunian and ejected objects (blue), plotted against time. The left (right) panel shows the results from the forward (backward) integration.

6.1 A traversal of the Solar system

Fig. 14 shows how the 70th clone of 2002 FY36 evolved in the forward direction. It has initial orbital elements of $a = 28.949$ au, $e = 0.124$, $i = 5\overset{\circ}{.}43$. This is a particularly interesting clone since it starts the simulation purely under the control of Neptune, and slowly works its way in through the Solar system, becoming a short-period

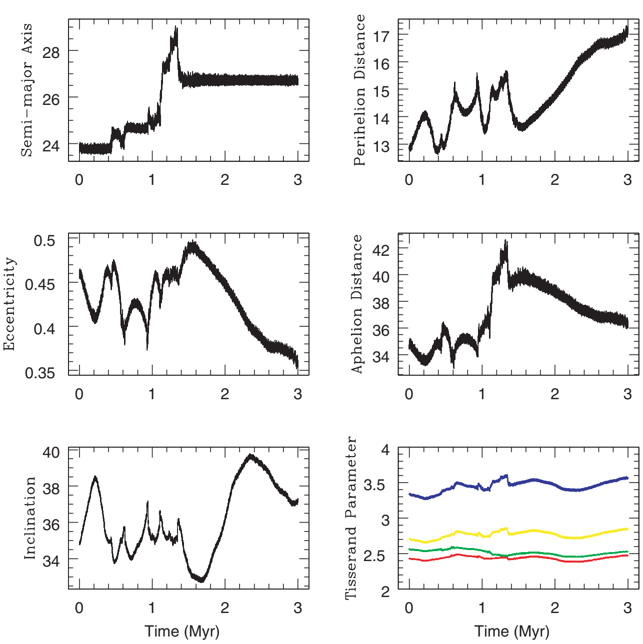

Figure 12. The behaviour of the 334th clone of 2000 FZ53 in the forward direction. The endpoint of the evolution of the clone is the 3 : 5 mean-motion resonance with Uranus.

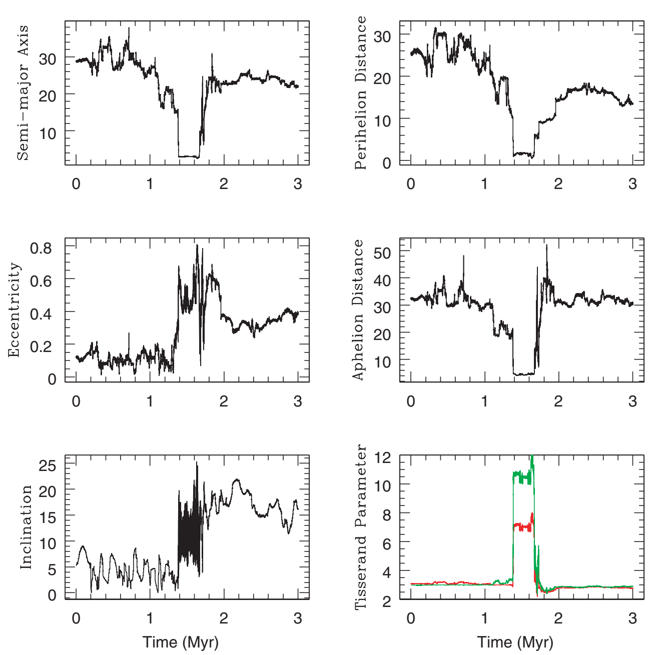

Figure 14. The evolution of the 70th clone of 2002 FY36 in the forward direction. In the plot of the Tisserand parameters, the value of $T_{\rm U}$ is shown in red and $T_{\rm N}$ in green. Note that the clone travels inwards to become an Earth-crosser (albeit briefly) before returning to the outer Solar system.

comet, and then works its way back out to a reasonably stable region. Initially, the perihelion of the object is gradually handed down to Uranus. Then, the influence of Uranus (just after the 1-Myr mark) acts to switch the perihelion and aphelion of the object around, so that it has aphelion near Uranus and perihelion near Saturn. Another perihelion–aphelion interchange happens at Saturn, handing the object down to the control of Jupiter. Jupiter then acts almost immediately again to interchange the perihelion and aphelion of the object, injecting it to the inner Solar system. Once there, it resides on a series of fairly stable orbits for just over 200 kyr, before becoming Earth-crossing and then being handed back outwards through another perihelion–aphelion interchange at Jupiter. At around 1.75 Myr, Saturn moves the perihelion away from the control of Jupiter and moves the aphelion to the control of Neptune. The object then spends the remaining 1 Myr of the integration in an orbit whose perihelion gets detached from Saturn by the effects of Neptune at aphelion, and which is reasonably stable.

6.2 A mean-motion resonance with Neptune

Fig. 15 shows the orbital evolution of the 12th clone of 2002 FY36 in the forward direction. The initial orbital elements of this clone were $a = 28.949$ au, $e = 0.104$ and $i = 5\overset{\circ}{.}37$. This clone is captured into a resonance when its semimajor axis is just over 40 au. This is close to both the 1 : 3 resonance with Uranus and the 7 : 11 resonance with Neptune. While in the resonance, the eccentricity (and hence the perihelion q and aphelion Q distance) of the clone is remarkably stable, as, to a lesser extent, is the inclination. This is likely an artefact of the lack of perturbing objects beyond Neptune. In practice, the effect of perturbations of massive bodies in the Edgeworth–Kuiper belt is likely to decouple such objects from Neptune altogether (and obviously, given that such behaviour is time-reversible, lead to the injection of fresh objects from such areas).

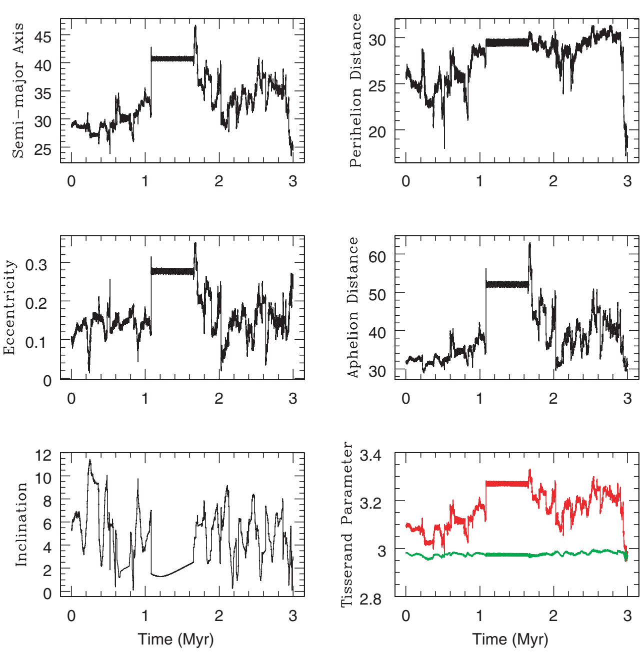

Figure 15. The evolution of the 12th clone of 2002 FY36 in the forward direction. Note the prolonged mean-motion resonance between roughly 1.1 and 1.6 Myr.

7 CONCLUSIONS

We have presented 3-Myr integrations of the orbits of clones of five Centaurs – namely, 1996 AR20, Chiron, 1995 SN55, 2000 FZ53 and 2002 FY36. At the start of the integrations, there is one object with perihelion under the control of Jupiter (1996 AR20), two under the control of Saturn (Chiron and 1995 SN55), and one each under the control of Uranus (2000 FZ53) and Neptune (2002 FY36). As the simulation evolves, clones of the Centaurs diffuse throughout the Solar system. This is illustrated by the behaviour of the number of clones controlled by each planet over time. The examples presented here are just a small number from the grand total of 23 328 Centaur orbit integrations carried out for our statistical analysis (Horner et al. 2004, or Paper I).

There are a number of generic patterns of behaviour identified from the simulations and illustrated by our examples. Every Centaur produces some clones which show short-period cometary activity during the 3-Myr evolution. Chiron has over 60 per cent of its clones becoming short-period objects, while 1995 SN55 has over 35 per cent. Clones of these Centaurs typically make numerous close approaches to Jupiter. At the other extreme, 2000 FZ53 has $\sim$2 per cent of its clones becoming short-period objects. It has been argued that the injection of a large Centaur like Chiron or 1995 SN55 into the inner Solar system will produce major biological and climatic trauma on the Earth (e.g. Bailey, Clube & Napier 1990; Hahn & Bailey 1990). If a clone becomes a short-period object, then it is likely to have repeated bursts of short-period activity – on average $\sim$30 or so in our simulations. Chiron is likely to be such a serial offender, as its blue colours probably point to a spell of short-period cometary activity in the recent past. Further such forays into the inner Solar system may well take place in its future.

About 20 per cent of the clones which become short-period comets then go on to become Earth-crossing. The idea that cometary bodies may populate the Earth-crossing asteroid families can be traced back to Öpik (1963). This is not the only source of near-Earth objects (NEOs), as asteroids in the Main Belt lying near the 3 : 1 resonance with Jupiter can also be transferred to Earth-crossing orbits (e.g. Wisdom 1983, 1985). Estimates of the fraction of NEOs emanating from the Main Belt vary between 40 per cent (Wetherill 1988) and $\gtrsim$80 per cent (Ipatov 1999, Bottke et al. 2002). None the less, the evidence that some dead comets become NEOs is strong. For example, the near-Earth asteroids 2201 Oljato and 3200 Phaethon are convincing cometary candidates, either on the grounds of surface composition (McFadden, Gaffey & McCord 1984) or of links to known meteor showers (Whipple 1983). Our calculations suggest that one Centaur becomes Earth-crossing for the first time approximately every $\sim$880 yr (see Paper I). The example presented in this paper is a possible evolutionary pathway for the largest known Centaur 1995 SN55, which has a diameter between 170 and 380 km. This emphasizes the possible dangers of objects emanating from the Centaur region – Centaurs are typically larger and more massive than asteroids. Even if they are not the major contributor to the near-Earth population in numbers, their contribution to the high-mass end is likely to be overwhelming.

A number of our Centaur clones become trapped at 1 : 1 mean-motion resonances around the giant planets. Here, we presented an example of a clone of 1996 AR20 which spends 0.5 Myr in a tadpole orbit around the 1 : 1 resonance with Jupiter. Studies of the origin of the Jovian Trojans usually assume that they are primordial. During the early stages of the formation of Jupiter, planetesimals are trapped into the changing gravitational field around the growing planet. Mutual collisions or energy losses due to gas drag may drive trapped planetesimals deeper into stable Trojan orbits (e.g. Shoemaker, Shoemaker & Wolfe 1989; Marzari, Tricarico & Scholl 2003). Based on our orbital integrations, an entirely new supply route is possibly, namely the capture of Centaurs. This may be tested by looking for out-gassing from Jovian Trojans, as any recently captured Centaurs may still contain volatiles. The supply route works for the other giant planets as well. An example of a clone of Nessus captured into a horseshoe orbit around the 1 : 1 resonance with Uranus will be presented elsewhere. This suggests that the Trojan populations of all the giant planets may be partly sustained by the flux of Centaurs.

The net flux of the Centaur population is inward, as the primary source is the Edgeworth–Kuiper belt while Jupiter tends to eject the objects from the Solar system over the course of time. None the less, examples of outward migration of individual clones often occur in the simulations, as illustrated by particular clones of Chiron, 1995 SN55 and 2002 FY36 in this paper. The former is particularly remarkable as it moves all the way in to Earth-crossing, before moving all the way back out to beyond Saturn. A burst of short-period cometary activity is followed by a return to the domain of the Centaurs. Such repeated traversals of the Solar system are a defining characteristic of the Centaur population, which is therefore expected to include objects encompassing a wide range of differing physical and dynamical characteristics.

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